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RESULTS OF WIND TUNNEL TESTS ON A FLIGHT PATH ACCELEROMETER AT MACH NUMBERS FROM 0.2 TO 3.0

James C. Uselton and T. O. Shadow

ARO, Inc.

February 1972

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FOREWORD

The work reported herein was done at the request of the Air Force Flight Test Center (AFFTC), Air Force Systems Command (AFSC), under Program Element 65701F, Project 6903, Task 55.

The test results were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), AFSC, Arnold Air Force Station, Tennessee, under Contract F40600-72-C-0003. The tests were conducted on June 7 and August 18, 1971, under ARO Project Nos. VA0078 and PC0152, and the final data were transmitted to the Air Force Flight Test Center on August 25, 1971. The manuscript was submitted for publication on October 6, 1971.

This technical report has been reviewed and is approved.

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ABSTRACT

A program was conducted at the Arnold Engineering Development Center (AEDC) to design, fabricate, and test new full-scale angle-of-attack and sideslip vanes for the newly developed flight path accelerometer (FPA) to alleviate the dynamic stability problem of the previous vanes. The investigation was conducted in the von Kármán Gas Dynamics Facility (VKF) Supersonic Wind Tunnel (A) and in the Propulsion Wind Tunnel Facility (PWT) Aerodynamic Wind Tunnel (4T). From dynamic stability tests of several vane configurations, the best performance vanes were selected and a position error calibration of these vanes was obtained at Mach numbers from 0.2 to 3.0 over a Reynolds number range based on boom diameter from 0.16×10^6 to 1.14×10^6. The angle of attack ranged from -3 to 24 deg. The selected vanes were dynamically stable over the entire Mach number range. The calibration data showed that generally the position error of the vane-indicated angles is less than 1.5 deg at maximum angle of attack and that the angle-of-attack vane-indicated angles are not affected by combined pitch and yaw attitude.

CONTENTS

ILLUSTRATIONS

NOMENCLATURE

AR	Aspect ratio, $(AR = b^2/s)$
b	Vane span length, in.
M_∞	Free-stream Mach number
p_o	Tunnel stilling chamber pressure, psia
q_∞	Free-stream dynamic pressure, psia
Re/in.	Free-stream unit Reynolds number per inch
r	Radius, in.
S	Vane planform area, in.^{2}
T_o	Tunnel stilling chamber temperature, °R
α_e	Angle-of-attack position error, $\alpha_t - \alpha_i$, deg
α_i	Angle of attack of model centerline as indicated by the model instrumentation, deg
α_t	Angle of attack of model centerline as indicated by the wind tunnel instrumentation, deg
β_e	Sideslip position error, $\beta_t - \beta_i$, deg
β_i	Sideslip angle of model centerline as indicated by the model instrumentation, deg
β_t	Sideslip angle of model centerline as indicated by the wind tunnel instrumentation, deg
ϕ	Model roll angle, deg

SECTION I
INTRODUCTION

In 1970, the Air Force Flight Test Center (AFFTC), Edwards Air Force Base, California, obtained a newly developed flight path accelerometer (FPA) to be used in the flight testing of newly developed aircraft. Calibration tests to determine the position error of the angle-of-attack and sideslip vanes of the FPA were attempted in the PWT-4T tunnel in July 1970. These tests were unsuccessful because of excessive vane vibration caused by vane dynamic instabilities. Viscous dampers were added to the FPA system, and a successful calibration was obtained. However, the viscous dampers increased the response time of the vanes to an intolerable level. The problem was brought to the attention of VKF personnel, and subsequently, an agreement was made that the VKF would investigate the problem and attempt to solve it by changing the vane aerodynamic shape.

The initial vanes had a 45-deg sweep angle with a high aspect ratio. A survey of the available literature confirmed the instability of this type of vanes and indicated that a larger sweep angle ($\approx$60 deg) and a lower aspect ratio ($<$2) were required to ensure dynamic stability. Several vane configurations were designed and fabricated by VKF. Dynamic stability tests were conducted on these different configurations at a Mach number of 0.3 in the VKF Tunnel A. From the dynamic test results, the best vane design was selected, and the position error calibration data were obtained.

Final position error calibration tests were conducted in the PWT Tunnel 4T at M_∞ = 0.2 to 1.3 and the VKF Tunnel A at M_∞ = 1.5 to 3.0 over a Reynolds number based on boom diameter from 0.16 x 10^6 to 1.14 x 10^6. The angle of attack ranged from -3 to 24 deg.

SECTION II
APPARATUS

2.1 TEST ARTICLE

A schematic of the full-scale FPA is shown in Fig. 1. It is designed for installation on the nose boom of flight test aircraft. The boom is equipped with two angle-of-attack vanes and one angle-of-sideslip vane. The vanes are mounted on shafts which ride internally on precision low-friction ball bearings. The vanes rotate freely within specified limits on

their respective hinge lines and, therefore, remain aligned with the local flow direction regardless of the boom angle of attack.

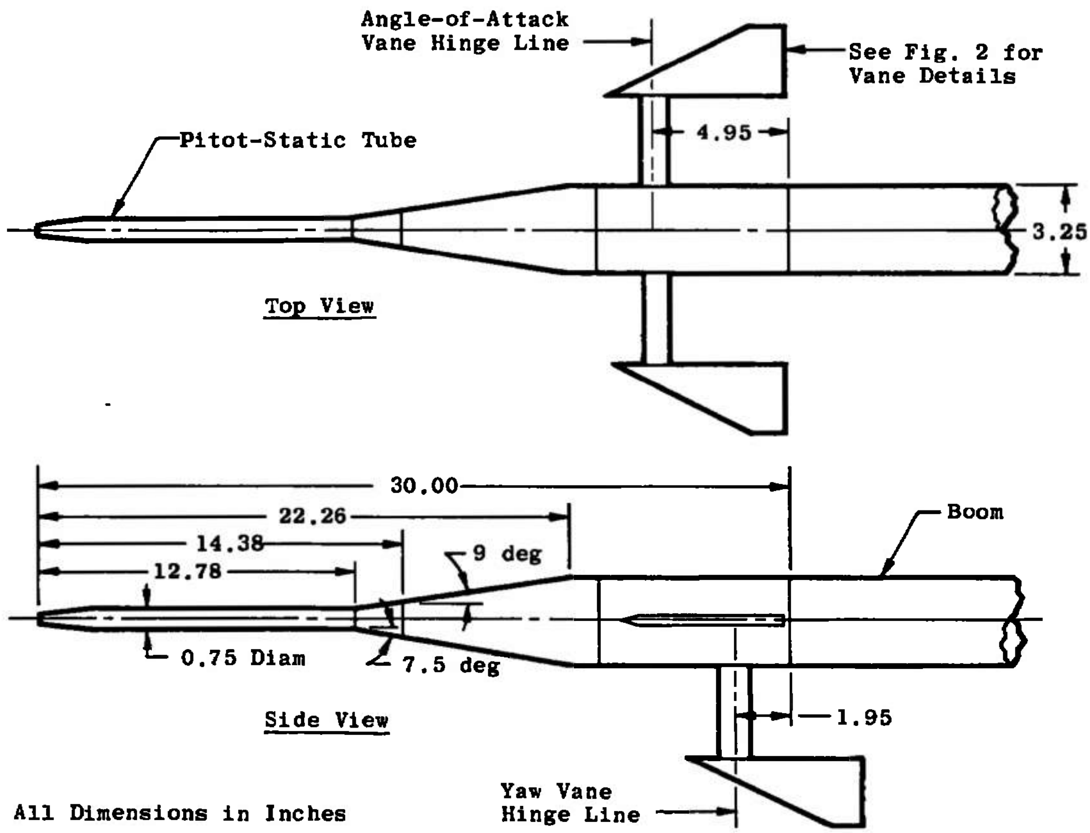

Fig. 1 Schematic of Flight Path Accelerometer

The details of the various vane configurations are shown in Fig. 2. Configurations 1, 2, and 3 use a common delta wing, with the hinge line at different axial locations. Configuration 1 has the hinge line at 25.8 percent of the root chord aft of the leading edge. Configurations 2 and 3 have the hinge line forward of the leading edge at 50 and 100 percent of the root chord, respectively. Configuration 4 is a wedge cross-section wing with 60.0-deg swept leading and trailing edges. Configuration 5 uses the same wing as Configuration 4 on a strut mount. A photograph showing the different vane configurations is presented in Fig. 3, and a photograph of the FPA with the Configuration 1 vanes attached is shown in Fig. 4. All the vanes were designed, fabricated, and statically balanced by the VKF. The reasons for the particular configurations chosen are presented in Section 4.1.

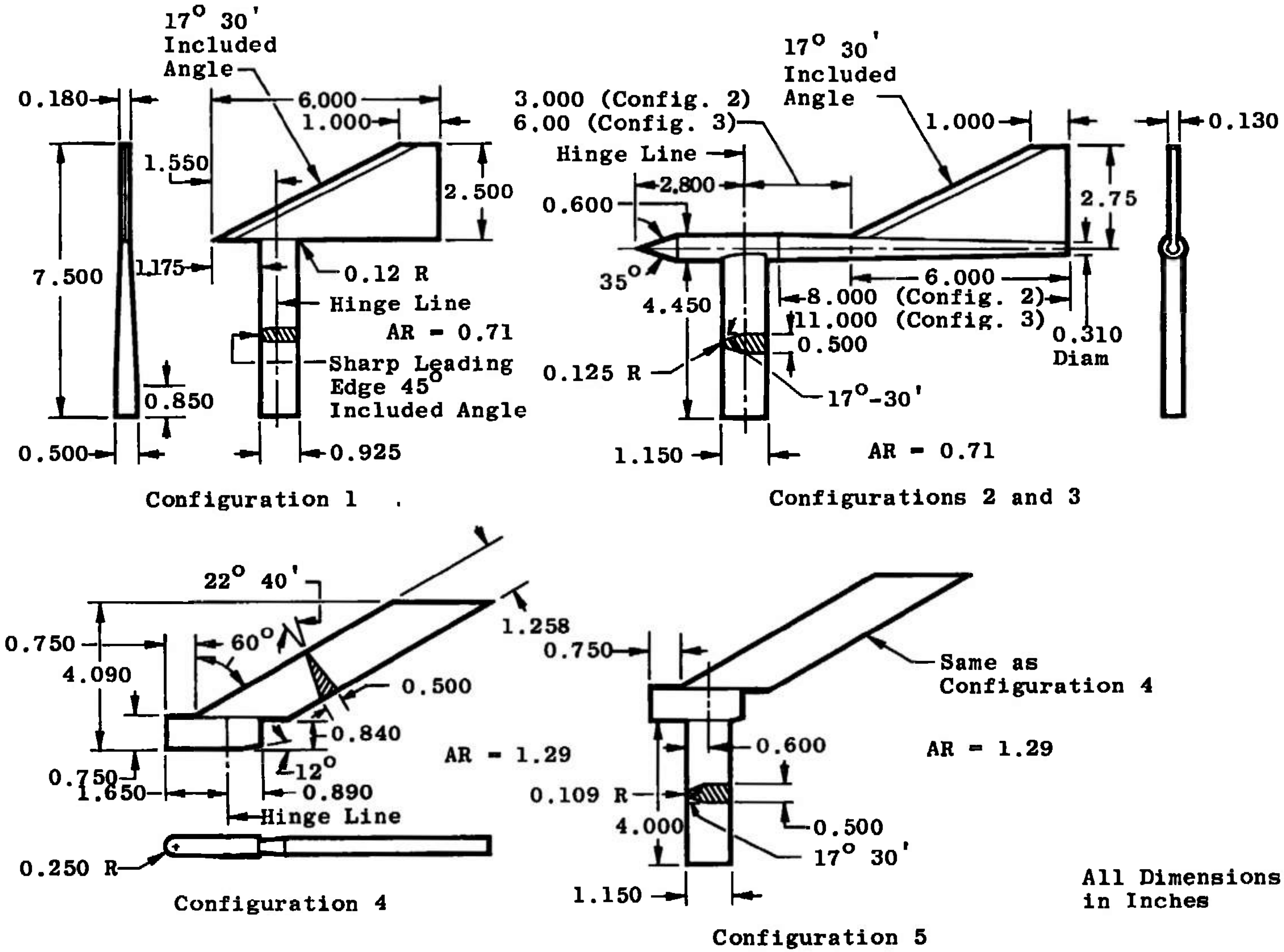

Fig. 2 Flight Path Accelerometer Vane Details

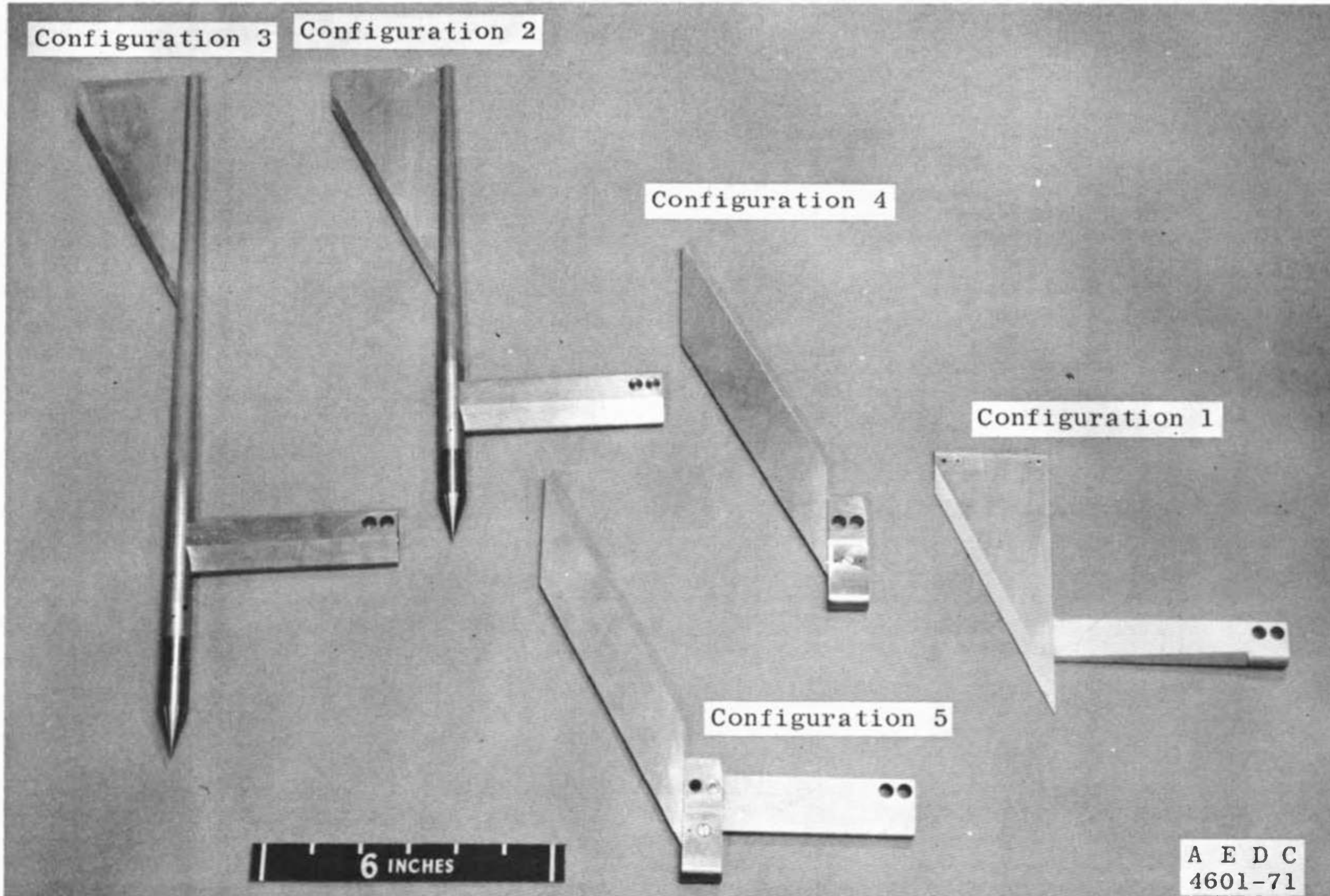

Fig. 3 Photograph of the Vane Configurations

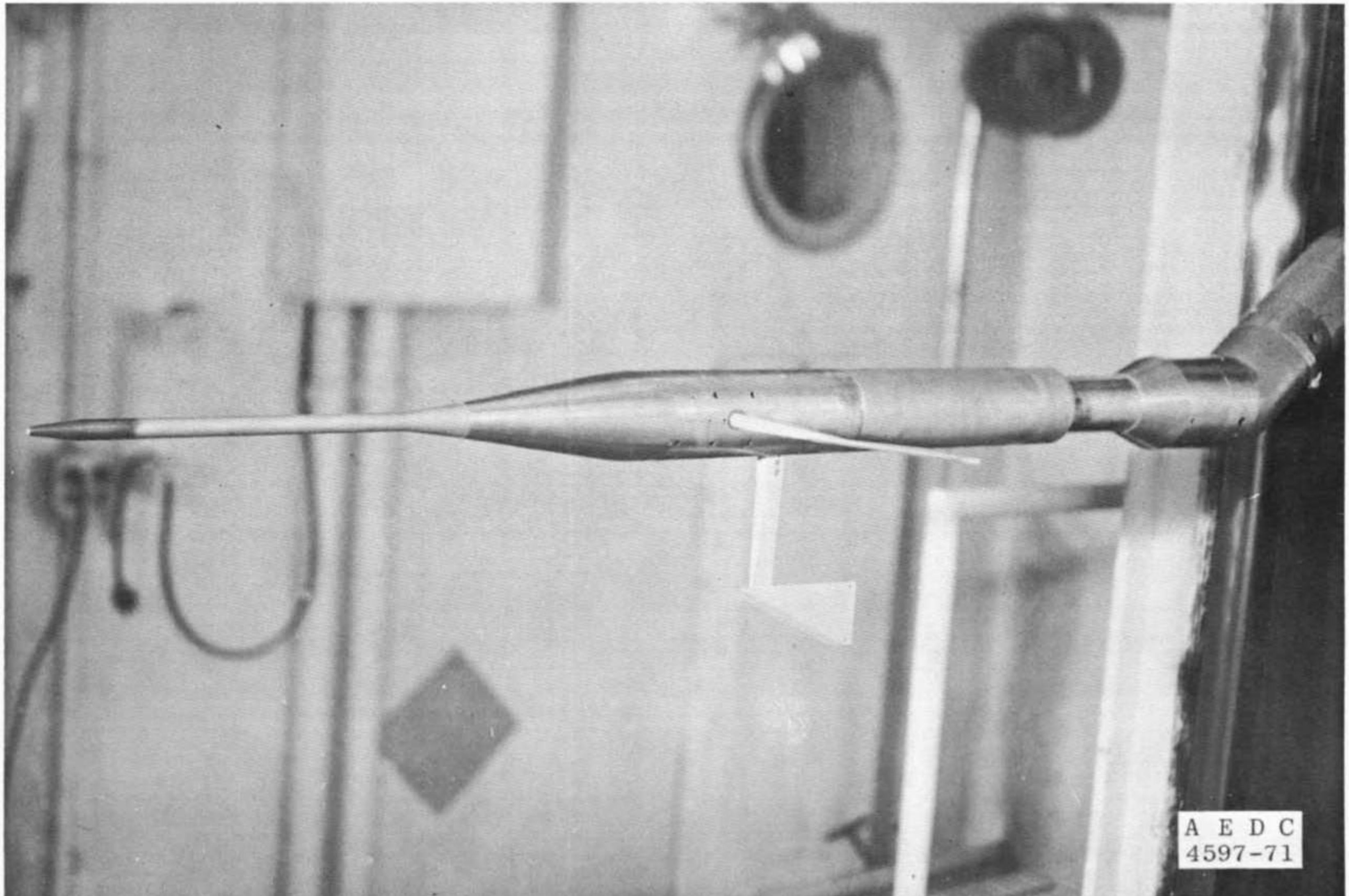

Fig. 4 Photograph of the Flight Path Accelerometer with the Configuration 1 Vanes Attached

2.2 WIND TUNNELS

Tunnel A is a continuous, closed-circuit, variable density wind tunnel with an automatically driven, flexible-plate-type nozzle and a 40- by 40-in. test section. The tunnel can provide supersonic Mach numbers from 1.5 to 6 at maximum stagnation pressures from 29 to 200 psia, respectively, and stagnation temperatures up to 750°R ($M_\infty = 6$). Minimum operating pressures range from about 1/4 to 1/20 of the maximum at each Mach number. The tunnel can also provide subsonic Mach numbers.

Tunnel 4T is a closed-loop, continuous-flow, variable density tunnel. It can be operated to provide Mach numbers from 0.20 to 1.30 with stagnation pressure from 2 to 26 psia at all Mach numbers. The test section is 4 ft square and 12.5 ft long with variable porosity walls (0 to 10 percent) and top and bottom walls that can be diverged or converged ±0.5 deg. The test section is completely enclosed in a plenum chamber from which the air can be evacuated, thus allowing part of the airflow to be removed through the test section walls. This design allows control of wave attenuation and blockage effects.

2.3 INSTRUMENTATION

The instrumentation contained in the FPA housing is as follows: An angle-of-attack synchro, and angle-of-sideslip synchro, two accelerometers, a temperature sensor, total and static pressure lines. The angle-of-attack and sideslip synchros measure the indicated angle of attack and sideslip of the FPA by measuring the angle of rotation of the vane shaft with respect to the FPA housing. The two accelerometers are mounted on the angle-of-attack vane shaft. The sensitive axis of one is normal to the shaft and in the plane of the vanes and is referred to as the longitudinal accelerometer. The sensitive axis of the other is normal to the plane of the vanes and is referred to as the normal accelerometer.

The outputs of the accelerometers, temperature sensor, and the pressure sensor were not required for these tests and were not recorded. The outputs of the angle-of-attack and sideslip synchros and the reference voltage were recorded on the standard Tunnel A and 4T d-c readout equipment. The boom angle of attack was recorded using the standard tunnel sector readout.

SECTION III
TEST PROCEDURE

3.1 TEST TECHNIQUE

The pitch oscillation data were obtained in Tunnel A at subsonic speeds by deflecting the alpha vanes to 5 deg by an air jet directed at the vane from below and behind and then rapidly shutting off the jet. The decay of the angle of attack for this phase of the tests was recorded, both on an oscillograph and on the Tunnel A instrumentation at the rate of 350 points per second. The vane damping data were obtained in Tunnel A at the conditions listed below:

M_∞	p_o, psia	T_o, °R	Re/in.	q_∞, psia
0.3	3.0	560	390	0.17
0.3	8.2	↓	1100	0.51
0.3	13.2	↓	1800	0.83
0.6	4.2	↓	1000	0.83
0.6	8.3	↓	2000	1.71
0.6	12.1	↓	3000	2.62

For the position error calibration, the boom was set to the specified angles in Tunnels A and 4T, and the readings from the FPA were recorded under static conditions. The position error calibration was obtained at the nominal conditions below:

M_∞	p_o, psia	T_o, °R	Re/in. x 10^{-6}	q_∞, psia	AEDC Tunnels
0.2	10.4	574	0.07	0.28	PWT 4T
0.3	4.8	568	0.05	0.29	↓
0.4	9.42	574	0.13	0.95	↓
0.6	4.75	567	0.09	0.91	↓
0.6	10.74	576	0.20	2.13	↓
0.8	7.2	568	0.16	2.12	↓
0.8	20.0	581	0.43	5.9	↓
0.9	6.3	569	0.15	2.1	↓
0.9	11.2	583	0.27	3.8	↓
1.1	9.5	578	0.23	3.75	↓
1.1	14.8	590	0.34	5.9	↓
1.3	8.8	581	0.21	3.7	↓
1.3	13.8	589	0.33	5.9	↓

M_∞	p_o, psia	T_o, °R	Re/in. x 10^{-6}	q_∞, psia	AEDC Tunnels
1.5	4.3	560	0.11	1.86	VKF A
1.5	13.5	↓	0.33	5.79	↓
2.0	5.9	↓	0.11	2.11	↓
2.0	16.2	↓	0.33	5.80	↓
2.5	20.8	↓	0.33	5.32	↓
3.0	28.9	↓	0.35	4.96	↓

3.2 DATA PRECISION

Uncertainties (bands which include 95 percent of the calibration data) in the basic tunnel parameters, p_o, T_o and M_∞, were estimated from repeat calibrations of the instrumentation and from the repeatability and uniformity of the test section flow during tunnel calibrations. These uncertainties were then used to estimate uncertainties in other free-stream properties using the Taylor series method of error propagation (Ref. 1). The calibrated uncertainties are:

	±Uncertainty, percent				
M_∞	M_∞	p_o	T_o	q_∞	Re/in.
0.2	0.18	0.3	0.75	0.45	0.44
0.3	0.18	↓	↓	0.46	0.95
0.4	0.17	↓	↓	0.43	0.94
0.6	↓	↓	↓	0.40	0.95
0.8	↓	↓	↓	0.36	0.96
0.9	↓	↓	↓	0.35	0.96
1.1	0.48	↓	↓	0.43	0.95
1.3	0.12	↓	↓	0.31	0.96
1.5	0.67	0.74	0.72	0.76	1.26
2.0	0.50	0.62	↓	0.76	1.22
2.5	0.31	0.48	↓	0.96	1.27
3.0	0.40	0.35	↓	0.68	1.18

Measurements of the model attitude in pitch and yaw using the tunnel sectors are precise within ±0.05 deg based on repeat calibrations. The data were corrected for tunnel flow angularity.

SECTION IV
RESULTS AND DISCUSSION

4.1 VANE DESIGN CONSIDERATIONS AND SELECTION

As discussed in Section I, previous tests on the original FPA vanes indicated that the vanes were dynamically unstable without the viscous dampers. The viscous dampers did stabilize the vanes, but they also increased the vane response time to undesirably high values. Therefore, it was decided to attempt to correct the problem by aerodynamically redesigning the vanes to make them dynamically stable.

The previous vanes had a wedge cross section with 45-deg swept leading and trailing edges similar to Configuration 4, except for the sweep angle. Both theoretical estimates and experimental data (Ref. 2) indicate that the wing aspect ratio should be approximately 2 or less for dynamic stability over the required Mach number range. The original vanes had an aspect ratio equal to 3.6, and therefore, for a simple solution while maintaining the same type vane, new vanes were made with 60-deg swept edges (Configuration 4) which had an aspect ratio of 1.29.

AFFTC personnel stated that different type vanes would be acceptable if their damping characteristics were better. Tobak (Ref. 2) has shown both theoretically and experimentally that delta planform wings with low aspect ratios are the most dynamically stable. Also, it has been shown (Ref. 3) that cutting off the wing tips increases the stability. Therefore, a 60-deg swept delta wing with a cutoff tip and an aspect ratio of 0.71 was selected as the basic planform shape and was strut mounted at three different axial hinge line positions to make up Configurations 1, 2, and 3 (see Fig. 2). The strut mount was necessary to reduce the body flow interference on the vanes and thereby maintain a low position error.

The vanes were designed for near minimum inertias but had to, of course, be balanced about the hinge line, and the different axial positions of the delta wing necessitated different inertias. The main criteria for judging the performance of the different vanes is not the actual damping of the vane, but the time required for any oscillation to damp out which also involves the inertia term. Therefore, the time required for a step input to the wing angle to damp to half-amplitude (time to half-amplitude $= \frac{\text{constant x inertia}}{\text{damping}}$) was used as the criteria in evaluating the different

vanes. The half-amplitude times at M_∞ = 0.3, Re/in. = 390, were:

Configuration	AR	Time to half-amplitude, sec
1	0.71	0.70
2	0.71	0.74
3	0.71	0.84
4	1.29	1.06

Configurations 1, 2, and 3 had near the same half-amplitude time, but the half-amplitude time for the higher aspect ratio vane (Configuration 4) was approximately 50 percent larger. Configuration 1 was selected as the primary configuration, since it had the lowest half-amplitude time and has a simple support.

4.2 CALIBRATION RESULTS (CONFIGURATION NO. 1)

The variations of the angle of attack indicated by the FPA, α_i, with the true angle of attack of the FPA boom, α_t, are shown in Fig. 5. Similarly, the β_i variations with β_t are shown in Fig. 6. The data show that the FPA indicates angles of attack and sideslip angles that are too high at Mach numbers below 2.5. Neither the α_i nor β_i data show any effect of Reynolds number. Combined α_i and β_i data (ϕ = 30 and 60 deg) are also shown in Figs. 5 and 6 and indicate that α_i is not affected by combined pitch and yaw. The data do show that β_i is definitely affected by the combined attitude. Apparently, the effect of combined attitude on β_i is caused by flow interference from the angle-of-attack vanes which are mounted at a more forward axial position on the boom. For the mission requirements of the FPA, the angle-of-attack readout is much more important than the sideslip readout, and therefore, the α_i vanes were placed forward to ensure no interference from the angle-of-sideslip vane.

The angle-of-attack data in Fig. 5 at M_∞ = 1.1 show an indicated angle of attack of near 1 deg at α_t = 0. These data were checked and verified by film coverage. It is believed that the shock from the angle-of-sideslip vane strut is near the base of the α_i vanes at this Mach number, creating a higher pressure near the base and thereby causing the vane to turn and indicate the erroneous angle of attack. This bias will have to be accounted for in the actual use of the vanes at this Mach number.

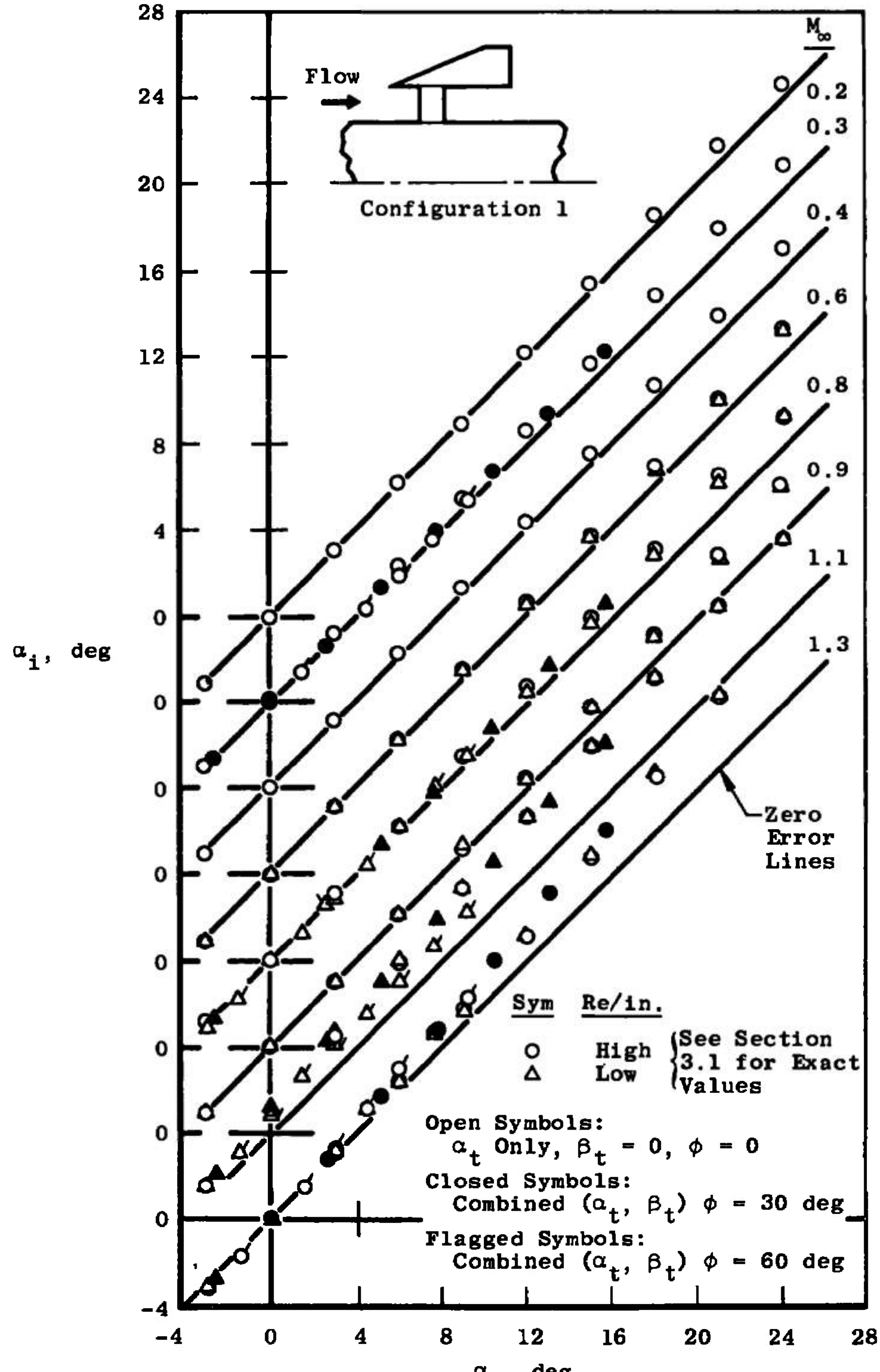

Fig. 5 Variation of the Indicated Angle of Attack, α_i, with the Actual Angle of Attack, α_t (Configuration 1)

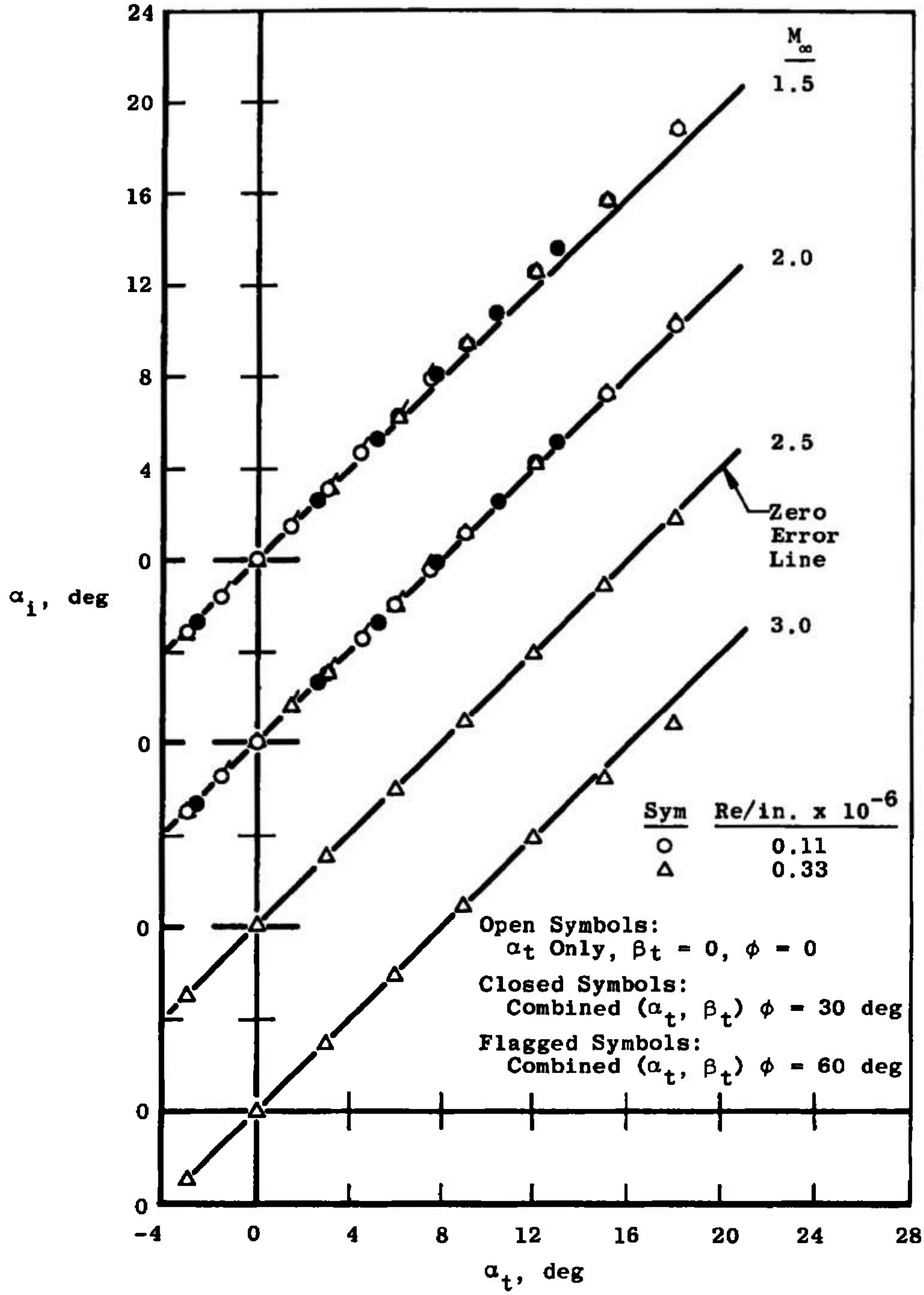

Fig. 5 Concluded

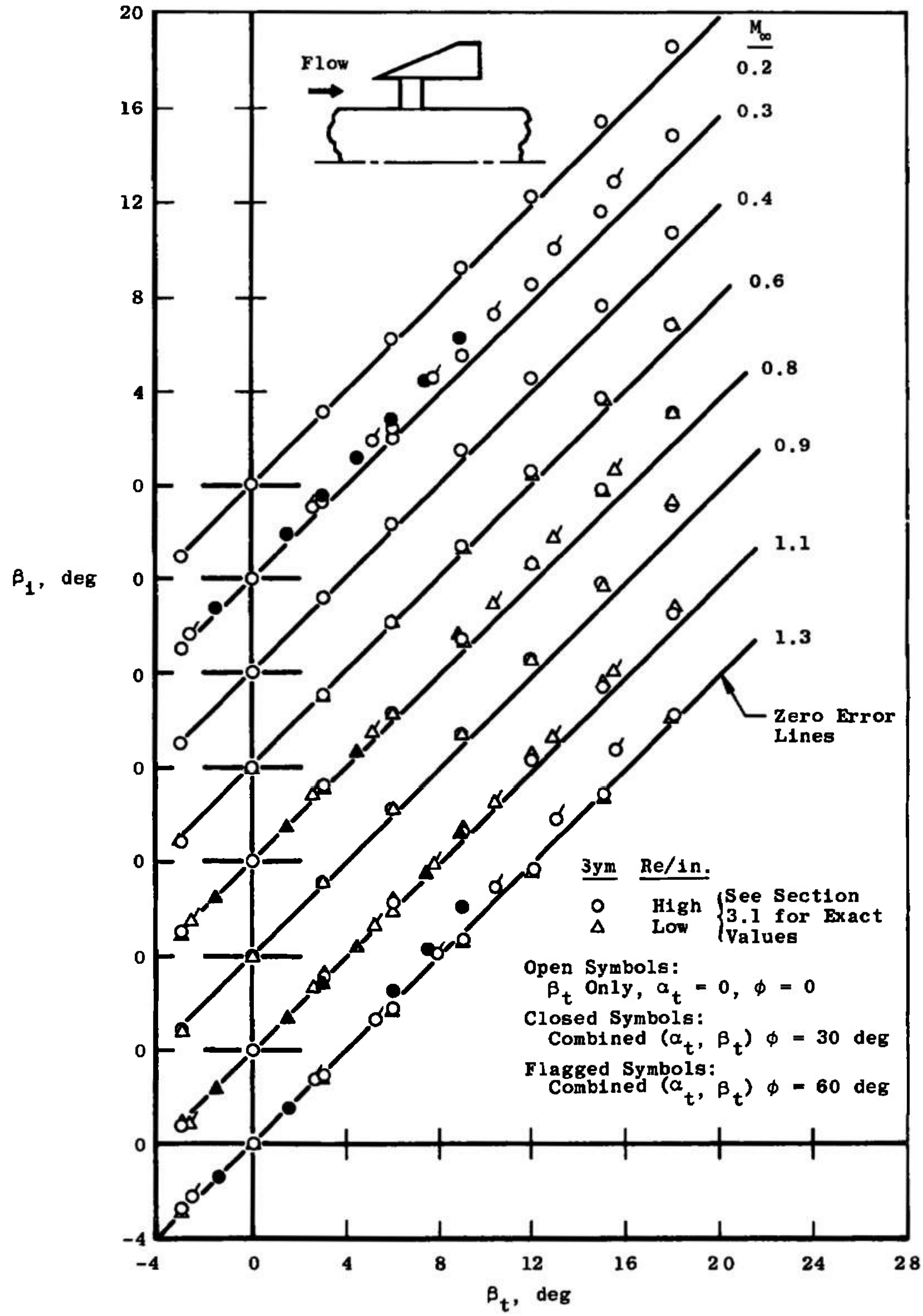

Fig. 6 Variation of the Indicated Angle of Sideslip, β_i, with the Actual Sideslip Angle, β_t (Configuration 1)

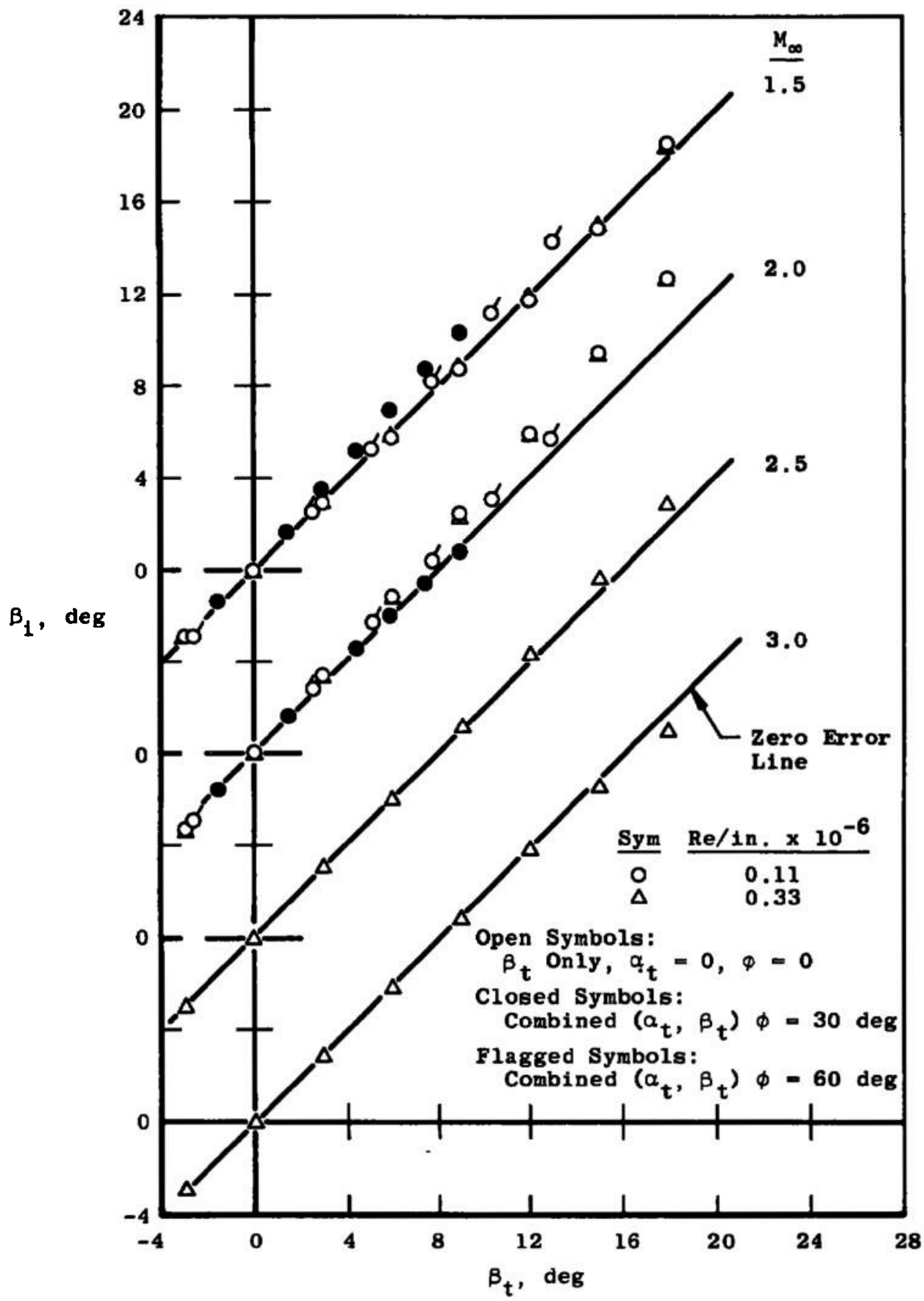

Fig. 6 Concluded

The ϕ = 0 data for the higher Reynolds number at each Mach number from Figs. 5 and 6 were used to obtain the position error angles, α_e and β_e, which are shown versus their corresponding indicated angles in Fig. 7. The angle-of-sideslip vane data show a position error that is generally less than 1 deg, except at M_∞ = 2.0 which has a near linear β_e that approaches 3 deg at β_i = 20 deg. The angle-of-attack position error is less than 1.5 deg except at M_∞ = 1.1 and 1.3, where α_e approaches 3 deg at α_i = 24 deg. The angle-of-attack position error angle is near linear for the majority of the Mach numbers at the lower angles of attack ($\alpha_i \leq 12$ deg).

SECTION V
CONCLUDING REMARKS

A program was conducted at the Arnold Engineering Development Center to design, fabricate, and test angle-of-attack and angle-of-sideslip vanes for a newly developed flight path accelerometer. The most stable set of vanes was selected, and calibration data were obtained at Mach numbers from 0.2 to 3.0 in the PWT 4T and VKF Tunnel A, respectively. The calibration data indicate the following:

1. The vane-indicated angles are high for Mach numbers less than 2.5 and $-3 \leq \alpha_i \leq 24$ deg.
2. The vane indicated angles show no effect of Reynolds number.
3. The angle-of-attack vane indicated angles show no effect of combined pitch and yaw attitude.
4. The sideslip vane indicated angles are affected by combined attitude.
5. At M_∞ = 1.1, the angle-of-attack vanes indicate an erroneous angle of ≈1 deg because of the shock from the angle-of-sideslip vane strut.
6. The position error of the angle-of-sideslip vane is less than 1 deg except for M_∞ = 2.0 where it approaches an error of 3 deg at β_i = 20 deg.
7. The position error of the angle-of-attack vanes is less than 1.5 deg at maximum angle of attack except at M_∞ = 1.1 and 1.3 where it approaches an error of 3 deg at α_i = 24 deg.

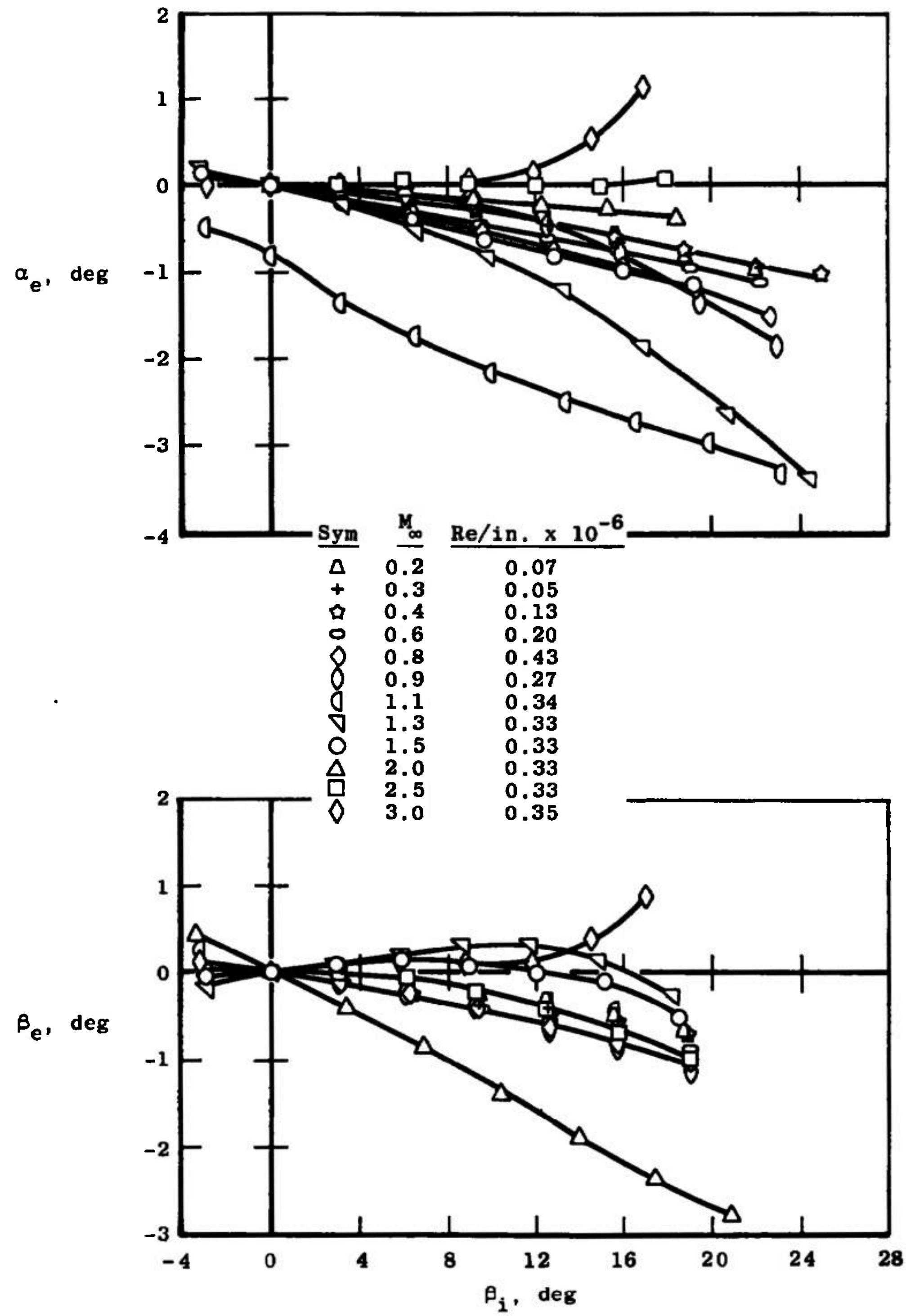

Fig. 7 Variation of the Angle-of-Attack Position Error and the Sideslip Angle Position Error with Their Respective Indicated Angles (Configuration 1)

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13. ABSTRACT

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